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by

Lewis A. Rossman
Wastewater Research Division
Water Engineering Research Laboratory
Cincinnati, Ohio 45268

and

Henry E. Haxo, Jr.
Matrecon, Inc.
Oakland, California 94623

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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# A RULE-BASED INFERENCE SYSTEM FOR PREDICTING LINER/WASTE COMPATIBILITY

Lewis A. Rossman* M. ASCE
Henry E. Haxo, Jr.**

Determining the chemical compatibility of a liner material for containment of wastes rests mainly on the application of expert opinion to interpret the results of short-term immersion tests. A methodology known as a production system is employed to encode such expert opinion into a structured evaluation procedure for PVC liners. The system consists of a collection of classification rules and scoring procedures for turning immersion test results into inferences on the likelihood of chemical incompatibility. Results for an illustrative PVC immersion test run are presented. Additional refinement of the production system and its extension to other liner materials is proposed.

## Introduction

Flexible membrane liners (FMLs) placed below wastes in a surface impoundment or landfill represent one component in an overall system of containment and control of hazardous liquids. Liner effectiveness is influenced by many factors related to waste characteristics and facility design and construction. Among the most significant of these is chemical compatibility - the ability of a liner material to maintain its functional capabilities when exposed to the waste it is to contain. This paper develops a systematic procedure for evaluating FML compatibility based on liner immersion test results.

There is presently no universally accepted method of testing FMLs for chemical compatibiltiy. It is sometimes possible to screen certain liner materials on the basis of past performance when the nature of the waste to be contained is well known. Compatibility matrices for combinations of liner - waste types can be found in U.S. EPA (3). When these are not applicable other methods are employed. Direct permeation measurements are generally not done. Instead liner materials are exposed to wastes over short time periods (4 to 12 months) while changes in certain compositional and physical properties are monitored over time. These properties include weight, volatiles content, extractables content, tensile strength, modulus, elongation, and hardness.

* Operations Research Analyst, Water Engineering Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268

** President, Matrecon, Inc., Oakland, California

Correlations between changes in the above properties and permeation of waste through the liner do not currently exist. Instead, exposure test results must be subjectively interpreted as indirect evidence of a liner's effectiveness. At the present state-of-the-art, selection of a satisfactory liner material for a given facility rests mainly on expert opinion. The objective of this paper is to demonstrate how such expert opinion can be formalized into a structured process that can be used by less experienced reviewers of liner compatibility. In this initial study it was decided to focus only on the chemical compatibility of polyvinyl chloride (PVC) liners. The second author of this paper supplied the necessary body of expertise on which the evaluation system is based. PVC compatibility criteria are developed from short term immersion test results only. Other determinants of overall liner effectiveness such as seam strength, quality of installation, and environmental stress cracking are not considered.

## PVC Behavior

Polyvinyl chloride (PVC) is an unvulcanized thermoplastic material produced by a polymerization process from vinyl chloride monomer. It is compounded with plasticizers (25 to 35%) to make it flexible and rubberlike. It also contains 1 to 5% of chemical stabilizers and various amounts of other additives. PVC liners are usually not fabric reinforced. They are the most widely used type of FML.

Chemical incompatibility of PVC liners with waste liquids can result in an absorption of waste material into the liner and/or an extraction of plasticizer out of the liner. Absorption behavior is characterized by a gain in weight and volatiles content as waste constituents migrate into the PVC. The resulting softening causes a loss in modulus (stress at a given percent elongation) to be observed. A loss of plasticizer from the PVC is characterized by an observed drop in extractable content. The resulting stiffening leads to an increase in modulus. Shrinking and consequent weight loss may or may not occur depending on whether other waste materials are exchanged with the plasticizer.

Another impairment to liner effectiveness can be a loss of elongation. Good elongation is needed so that the liner can stretch to accomodate shifting and uneven settlement of the soil and non-uniform size bedding aggregate.

## Evaluation Methodology

The foregoing discussion offers a qualitative view of some of the behavior modes of PVC chemical incompatibility. A more structured and quantitative procedure can be built on this foundation to help guide the the less experienced facility designer or permit reviewer in the liner evaluation process. A methodology known as a production system is proposed for this purpose. This will be a collection of classification rules and scoring procedures for turning observations (immersion test results) into conclusions (likelihood of chemical incompatibility).

In general, a production system consists of three principle components: a set of rules, a data base, and a control system (1). A rule is a simple conditional statement of the form: "If this condition holds, then take this action". For example, the rule "Order white wine with fish or fowl" might be encoded as "IF eating fish OR eating fowl THEN order white wine". In general the conditions and actions of production rules consist of propositions about the state of the world. The data base is a temporary store of information on the current status (truth or falsity) of the system's propositions. The control system dictates the order in which the rules are evaluated. A rule is evaluated by scanning the data base to see if its left hand side premises are satisfied. If they are, then the actions indicated on the right hand side are taken. This results in an updating of the data base.

A fourth element can be introduced, that of inexact reasoning. Instead of specifying that "If A is present then infer B with complete certainty" one may say "If A is present then infer B with some degree of certainty" where the degree of certainty may be weak, strong, etc. In addition, if premise "A" is itself uncertain, then the certainty of conclusion "B" should be reduced accordingly.

Production systems form the basis of what are known as expert systems. These are computer programs that handle real-world, complex problems requiring an expert's interpretation. They solve these problems using a model of human expert reasoning in the form of a production system. Their performance is such that they reach the same conclusion as would the human expert if faced with a similar problem. Over the past ten years expert systems have been developed to solve problems in chemical structure analysis, medical diagnosis, geological exploration, and computer configuration selection, among others (5).

## Immersion Test Data

A prototype first generation production system for evaluating PVC liner chemical compatibility has been developed. The system uses immersion test data to infer a likelihood of incompatibility, i.e., a tendency for the liner not to be effective in containing the waste over the design life of the facility. This liklihood is expressed on a scale of 0 to 1, with 0 representing no evidence of incompatibility and 1 indicating definite incompatibility.

The immersion test data used in the evaluation system is similar to that proposed in the U.S. EPA Method 9090 (4). Pieces of the liner are immersed with both sides exposed to the waste for a period of 120 days. Test runs are made at both room temperature and at 50 deg. C. Specimens of the liner are removed at monthly intervals and tested for certain analytical and physical properties. These same properties are also determined for an unexposed sample of the liner.

## PVC Liner Production System

The production system developed to evaluate the chemical compatibility of PVC liners attempts to identify the following problematic conditions: inadequate elongation retention, excessive plasticizer loss, excessive waste absorption, and projected violation of a serviceability limit. The first three types of behavior were discussed previously. The fourth represents changes in liner properties which should not be exceeded over the facility design life (e.g., the weight should not increase by more than 100%). These serviceability limits are associated with uses of PVC not necessarily related to waste containment. However it seems prudent to still apply them given the limited long term experience with PVC liners in hazardous waste facilities.

An overview of the production system is presented in the logic diagram of Figure 1. The boxes contain propositions about the state of the exposed liner as derived from the immersion test results. The degree of belief in the truth of these propositions can vary on a scale of -1 (definitely not true) to 0 (unknown) to +1 (definitely true). The diagram shows how certain propositions are connected by logical AND/OR relations to infer other propositions. The numbers in parentheses indicate the strength of the inference. These are called certainty factors (CF's).

The logic diagram of Figure 1 is another way of expressing the production rules described earlier. For example, the occurrence of the top-level condition in the diagram ("liner is incompatible") can be written as the following production rule:

IF there is an indication of inadequate elongation retention
OR there is an indication of excessive tendency towards plasticizer loss
OR there is an indication of excessive tendency towards waste absorption
OR there is a projected violation of a serviceability limit
THEN the liner is incompatibile (CF=1.0)

The overall degree of belief in incompatibility is equal to that of the most prominent problem behavior in the four premises of this rule (i.e., the one with the highest degree of belief). Additional rules are used to establish the strength of each of these four premises. For example, the "indication of excessive tendency towards waste absorption" is arrived at using the following rule sequence:

IF the weight gain is under 5 to 10 %
AND the final volatile content is less than 5 to 10 %
AND the extractable content drops less than 5 %
THEN there is evidence that the weight gain is mostly water (CF=0.8)

IF the weight gain is increasing by more than 1 %
AND the final volatile content increases to more than 5 to 10 %
AND there is NO evidence that the weight gain is mostly water
THEN there is analytical evidence of waste absorption (CF=0.8)

IF there is analytical evidence of waste absorption
AND the modulus loss is greater than 5 to 10 %
THEN there is an indication of excessive tendency towards waste absorption (CF=0.8)

The entire production system consists of twelve such rules. These are evaluated in two passes, one for the results at each immersion test temperature, using a "forward chaining" approach (5). Evaluation of the degree of belief in a rule's conclusion is based on its certainty factor and the belief in its premises using the procedures described by Shortliffe and Buchanan (2). Rules that involve serviceability limits are evaluated by extrapolating the immersion test results to estimate the time at which the limit would be exceeded. This estimate is then compared with the design life of the facility to assess the severity of violation.

## Illustrative Application

The data in Table 1 are immersion test results obtained by Matrecon, Inc. for a PVC placed in a waste mixture from an industrial operation. For the sake of illustration we assume that this PVC is being considered for use in an intermediate-term storage pond with a 5 year design life and a 10 deg. C exposure temperature.

When the PVC chemical compatibility production system was applied to this data it concluded that there was a moderate indication of incompatibility (degree of belief = .675). The findings leading to this conclusion can be summarized as follows:

i. there was no indication of excessive elongation loss,

ii. at 23 deg. C there was no indication of excessive plasticizer loss or waste absorption,

iii. at 50 deg. C the apparent absorption of volatiles was interpreted to be a water gain and thus a finding of excessive waste absorption could not be supported,

iv. the only problematic serviceability limit was for tensile loss, with a projected violation occurring after 2.3 years of service.

It was the latter finding that determined the overall compatibility rating.

## Recommendations for Future Work

The current production system for PVC liner compatibility evaluation should be considered a first-generation prototype. It will be necessary to subject the system to extensive testing and evaluation on various types of PVC materials, wastes, and facility designs. Both liner experts and hazardous waste engineers/planners should participate in the process. Opportunity to include their comments and suggestions as feedback to improving the system should be provided.

Based on the experience derived from the development of the current production system there are several issues which should receive particular attention in future evaluations:

i. If several problem behaviors are evident, should they all contribute to the conclusion of overall liner incompatibility or, as is done in the current system, only the most evident behavior?

ii. Is there a better way of employing the test results from the two different temperature exposures than is currently used?

iii. The current system requires both analytical and physical evidence to conclude there is a problem with either plasticizer loss or waste absorption. Is this too strict a criterion?

iv. The procedure used to extrapolate the immersion test results to predict behavior over the entire facility life is very speculative. Can a more theoretically or empirically appropriate method be found?

One particularly useful aspect of the system is the rational structure that it imparts to the difficult problem of liner test interpretation. This structure provides a focus for resolving differences of opinion that will inevitably arise as part of the evaluation process recommended above. It helps direct discussion towards specific technical issues and should hopefully serve to minimize the amount of unproductive argumentation. Pending successful evaluation of the methodology, consideration should be given to extending it to other types of liner materials to produce a truly comprehensive FML evaluation/design/review tool.

References

1. Davis, R. and J. King, "An Overview of Production Systems", Machine Intelligence, 8:300-332, (1977).

2. Shortliffe, E.H. and B.G. Buchanan, "A Model of Inexact Reasoning in Medicine", Mathematical Biosciences, 23:351-379, (1975).

3. U.S. Environmental Protection Agency, "Lining of Waste Impoundments and Disposal Facilities", SW-870, Office of Solid Waste and Emergency Response, Washington, D.C., (1983).

4. U.S. Environmental Protection Agency, "Compatibility Test for Wastes and Membrane Liners", Office of Solid Waste and Emergency Response, Washington, D.C. (1984).

5. Weiss, S. and A. Kulikowski, A Practical Guide to Designing Expert Systems, Rowman and Allanheld, (1984).

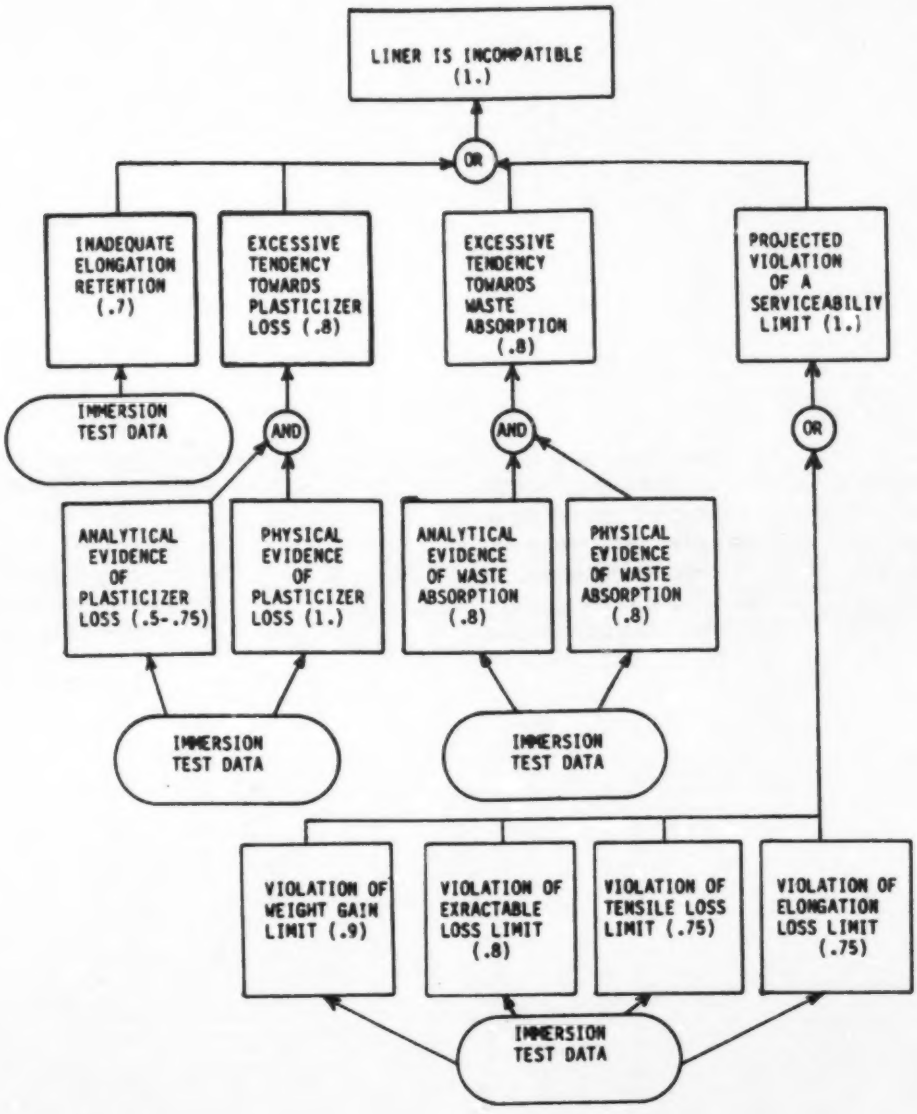
LINER IS INCOMPATIBLE (1.)
OR
INADEQUATE ELONGATION RETENTION (.7)
EXCESSIVE TENDENCY TOWARDS PLASTICIZER LOSS (.8)
EXCESSIVE TENDENCY TOWARDS WASTE ABSORPTION (.8)
PROJECTED VIOLATION OF A SERVICEABILIY LIMIT (1.)
IMMERSION TEST DATA
AND
AND
OR
ANALYTICAL EVIDENCE OF PLASTICIZER LOSS (.5-.75)
PHYSICAL EVIDENCE OF PLASTICIZER LOSS (1.)
ANALYTICAL EVIDENCE OF WASTE ABSORPTION (.8)
PHYSICAL EVIDENCE OF WASTE ABSORPTION (.8)
IMMERSION TEST DATA
IMMERSION TEST DATA
VIOLATION OF WEIGHT GAIN LIMIT (.9)
VIOLATION OF EXRACTABLE LOSS LIMIT (.8)
VIOLATION OF TENSILE LOSS LIMIT (.75)
VIOLATION OF ELONGATION LOSS LIMIT (.75)
IMMERSION TEST DATA

Figure 1. Logic Diagram of the PVC Liner Evaluation System

Table 1. Test Results for a PVC Immersed in an Industrial Waste

| Temperature, deg. C<br>Time, months | Original | 23<br>2 | 23<br>4 | 50<br>2 | 50<br>4 |
|---|---|---|---|---|---|
| Weight, % change | 0 | 0.9 | 1.2 | 5.1 | 7.5 |
| Volatiles, % | 0.15 | 0.83 | 1.45 | 1.57 | 7.05 |
| Extractables, % | 29.91 | 30.80 | 31.44 | 30.80 | 30.60 |
| Modulus, % retention | 100 | 101 | 87 | 96 | 83 |
| Elongation, % retention | 100 | 108 | 109 | 112 | 95 |
| Tensile, % retention | 100 | 101 | 94 | 96 | 85 |